

Observed HR diagrams and stellar evolution: the interplay between observational constraints and theory
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CMD's, RR Lyrae's, clump stars and reddening in the LMC

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Abstract.

We present new B , V , I photometry in the standard Johnson-Cousins photometric system of two regions near the bar of the Large Magellanic Cloud (LMC), one of which is very close to LMC field used for the "Coimbra test on the synthetic CMD techniques". The two areas contain 128 RR Lyrae variables and more than 8000 clump stars. Once combined with Clementini et al. 2001 (astro-ph/0007471) photometry the new data-set allows us to get (i) accurate CMD's down to $V \sim 23$ mag, (ii) full coverage of the B and V light variation for more than 80% of the RR Lyrae's, (iii) a very precise estimate of the LMC RR Lyrae's average apparent luminosity, (iv) an accurate estimate of the I luminosity of the LMC clump stars, and (v) an independent evaluation of the reddening in these regions of the LMC using the pulsational properties of the RR Lyrae's in our sample. A detailed comparison is made between our, OGLE II and MACHO photometries. We discuss the impact of our new results on the distance to the LMC and on the *short* and *long* distance scale controversy.

1. Introduction

Despite its vicinity and notwithstanding the enormous observational effort devoted to its study, many of the LMC properties (distance, reddening, star formation history, etc.) are not yet sufficiently well-known. Among them, the distance is by far the most controversial issue with a 0.2-0.3 mag difference between *short* and *long* scales provided by different distance indicators found to coexist in the LMC (e.g. Cepheids, RR Lyrae, clump stars, etc.). In the *short* distance scale, which is the scale favoured by the statistical parallaxes of field RR Lyrae variables and the Clump method, the distance modulus to the LMC is about 18.24 mag (Udalski 2000), the age of the galactic Globular clusters (GGCs) is about 16 Gyr, and the absolute luminosity of the RR Lyrae is about 0.7 mag. In the

long scale, which is the scale favoured by Cepheids and Main Sequence Subdwarf Fitting of GGCs, the distance modulus of the LMC is about 18.5 mag, the age of the GGCs is 13 Gyr, and the absolute magnitude of the RR Lyrae is about 0.5 mag (Carretta *et al.* 2000, and references therein).

Thanks to their pulsational properties combined with the almost constant absolute magnitude RR Lyrae variables have long been recognized to be excellent tracers of old stellar populations as well as primary distance indicators for the Local Group galaxies. About 8000 field RR Lyrae have been discovered in the LMC by the MACHO microlensing experiment (Alcock *et al.* 1996). We have observed two regions of the LMC bar which according to Alcock *et al.* (1996) were expected to host many RR Lyrae as well as a large number of clump stars. These data allowed us to study the photometric and pulsational properties of the RR Lyrae which fall in the 2 areas in great detail, to get a very precise estimate of the apparent luminosity of the Horizontal Branch (HB) and to measure the average metallicity of the LMC old stellar component as defined by its RR Lyrae stars. Finally we have also obtained an independent evaluation of the reddening in these fields of the LMC bar. The comparison between average luminosities of RR Lyrae and clump stars in the same area also allowed us a direct confrontation of the related distance scales. Our results directly bear upon the "Coimbra experiment", since provide independent informations on the distance modulus, the metallicity of the old stellar component and the reddening value, in the region of the bar of the LMC simulated by the different CMD techniques.

2. Observations and data reductions

Time series B , V , and I exposures of two 13×13 arcmin 2 fields (namely, Field A and B) close to the bar of the LMC and contained in Field #6 and #13 of the MACHO microlensing experiment (Alcock *et al.* 1996) have been obtained with the 1.5 Danish telescope at ESO, La Silla, in two observing runs respectively in January 1999 and 2001. Field A also has a 40% overlap with OGLE II field LMC_SC21 (Udalski *et al.* 2000) so that a star by star comparison is possible, for the first time, between these two photometries. The full data-set consists of 72, 41 and 15 frames in V , B and I respectively. 152 variables were identified in the two fields of which 128 are RR Lyrae's. Full coverage of the light curve has been obtained for more than 80% of them. We have also obtained low resolution spectra and measured the ΔS metal abundances (Preston 1959) for 6 of the 10 RRd falling in the sample, using EFOSC2 at the 3.6 m telescope. Data reduction of the photometric frames was performed using DoPHOT (Schechter, Mateo & Saha 1993) for the 1999 observations, and the DAOPHOT and ALLFRAME reduction packages (Stetson 1987, 1994) for the 2001 data.

Panel *a* of Figure 1 shows the V vs $(B-V)$ diagram of Field A from data taken in 1999, the remaining 3 panels show the V vs $(B-V)$, V vs $(V-I)$, and I vs $(V-I)$ diagrams for the 2001 data. Beside the higher sensitivity in V and B of the CCD used in 2001 (an EEV chip in 2001 and a Loral-Lesser CCD in 1999) and the better seeing and photometric conditions during the observations, a further improvement upon the 1999 photometry was achieved thanks to the use of the reduction packages DAOPHOT and ALLFRAME. The new HR diagrams reach about one magnitude fainter ($V_{limit} \sim 23$) with about 3 times as stars than

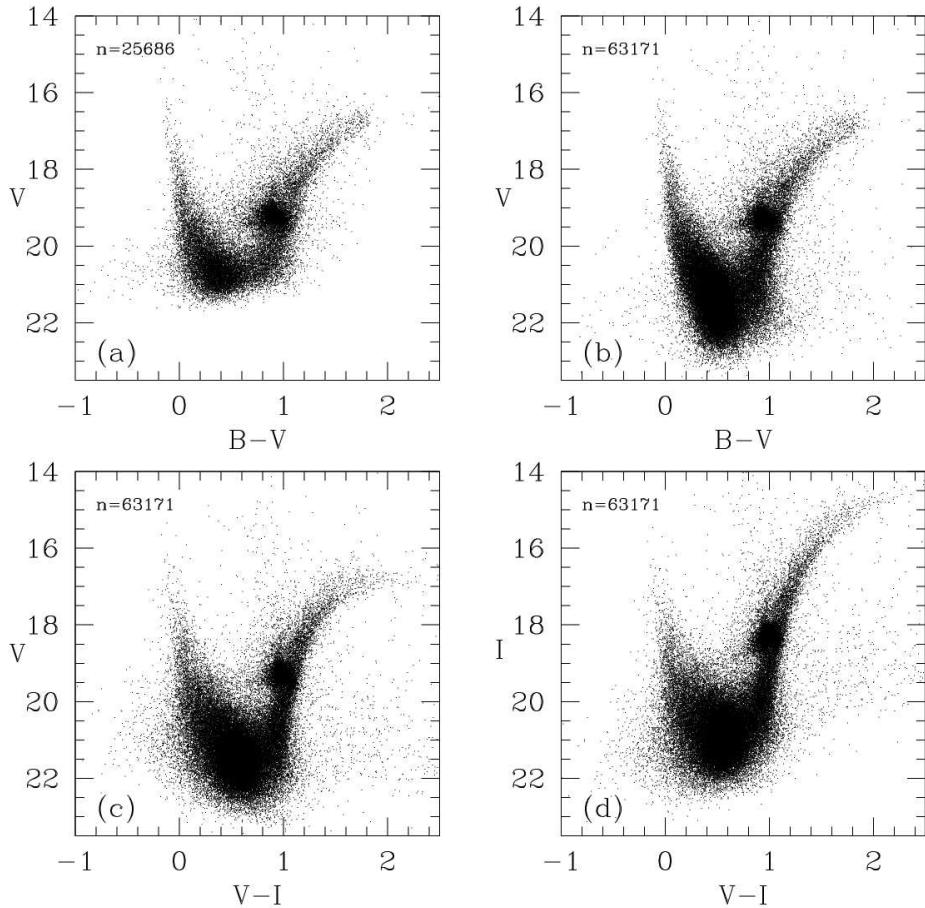


Figure 1. HR diagram of LMC Field A, from data in 1999 (panel *a*) and in 2001 (panels *b*, *c*, *d*), respectively.

in the 1999 data-set. V , B , and Δi light curves for some of the variables in our sample are shown in Figure 2. Perfect agreement is found between light curve data points corresponding to the two separate runs.

According to the period distribution of the RR Lyrae's in our sample, the LMC has properties intermediate between the Oosterhoff types I and II (Oosterhoff 1939). There is a small difference in the average luminosities of the RR Lyrae in the two fields which suggests that a 0.02 mag differential reddening may exist between the two areas.

The reddening is known to be patchy and vary from one region to the other of the LMC. A large number of different estimates exist in the literature with values in the range from 0.03 to 0.22 mag, depending on the region of the LMC and on the reddening indicator adopted. Since reddening is a major ingredient in any distance derivation procedure, it is particularly important to estimate the reddening in the same region of the distance indicators used to measure the distance to the LMC. Reddening in our two fields was derived from the compar-

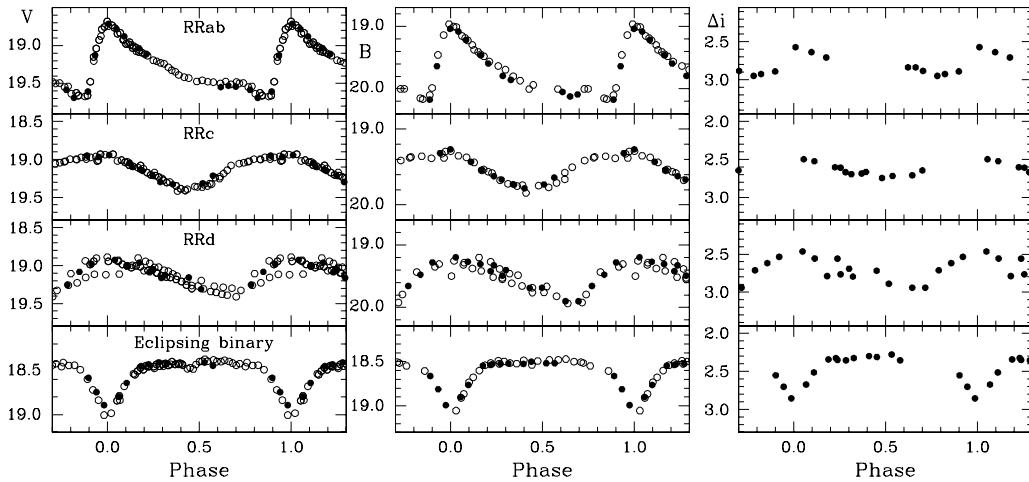


Figure 2. Some examples of our light curves. Open circles are from Clementini et al. (2001), filled dots are the new data points. Only differential light curves in the instrumental magnitude system are shown for the I band, since the calibration of the I data is still in progress.

ison of the colours of the edges of the instability strip defined by the RR Lyrae in our sample, with those of the Galactic globular cluster M3 ($[\text{Fe}/\text{H}] = -1.5$, $E(B-V) = 0.00$ mag) based on Corwin & Carney (2001) photometry. We derive values of 0.09 and 0.07 mag for Field A and B, respectively, and an upper limit average value of 0.10 mag. Our estimate is 0.044 mag smaller than derived in the same area by Udalski et al. (1999) using the I luminosity of the clump stars. The average properties, the metallicity (Bragaglia et al. 2001) and the reddening inferred from the RR Lyrae in our sample are summarized in Table 1.

Table 1. Average properties of the LMC RR Lyrae in our sample

$\langle P_{ab} \rangle$	Oo-type	$V(\text{RR})_{\text{FieldA}}$	$V(\text{RR})_{\text{FieldB}}$	$[\text{Fe}/\text{H}]$	$E(B-V)$
0.573	OoI/OoII	19.369 ± 0.023	19.314 ± 0.025	-1.5 ± 0.2	0.10

The comparison between the average luminosity of the RR Lyrae in our sample and literature values are summarized in Table 2.

Our dereddened average luminosity of the RR Lyrae is in very good agreement with Walker's (1992) value for the LMC cluster RR Lyrae's, and is 0.06-0.07 mag brighter than MACHO's. This difference may be due to the unconventional filter bands of the MACHO photometry. OGLE II's $\langle V(\text{RR}) \rangle_0$ is about 0.10 mag brighter than our estimate due to higher reddening value adopted by these authors. A star by star comparison is also possible with OGLE II based on the more than 5000 clump stars we have in common. Particularly important is the

Table 2. Comparison with the $\langle V(RR) \rangle_0$ values in the literature transformed to a common value of the metallicity: [Fe/H]=−1.5

$\langle V(RR) \rangle_0$	N _{stars}	Error			Reddening	Reference
		(1)	(2)	(3)	(total)	
19.03	93	0.02	0.03	0.06	0.07	0.10 Present work
19.03	182	0.04	0.025	0.05	0.07	0.09 Walker (1992)
19.095	500	—	0.073	0.06	0.10	0.1 MACHO (4)
18.92	71	0.04	0.015	0.08	0.09	0.144 OGLE II LMC_SC21 (5-6)
18.91	—	0.04	0.015	0.08	0.09	0.143 OGLE II (7)

(1)= standard deviation of the average, (2)=photometric zero point, (3)= absorption contribution

(4)= Alcock et al. (1996), (5) Udalski et al. (1999), (6) Udalski et al. (2000), (7)= Udalski (2000)

comparison of the average luminosities of RR Lyrae and Clump stars in the I band, since the I luminosity of the Clump is the method which provides the shortest distance to the LMC ($\mu_{LMC}(\text{Clump})=18.24$ mag, Udalski 2000). Our average I luminosity for the clump stars is 18.28 mag, to compare with Udalski's (2000) 18.25 mag.

However, it should be reminded that the Clump of a composite population, as the one in the LMC, has a complex structure resulting from the superposition of stellar populations with different masses and ages. Strong evolutionary and age effects are then present and should be properly accounted for when the Clump is used as a distance indicator. On the other hand, the contribution to the Clump by the horizontal branch (HB) of the *old stellar population* in the LMC is very well defined by its RR Lyrae's. The average luminosity of the RR Lyrae very clearly corresponds to the lowest envelope of the Clump. This is shown in Figure 3, that displays the enlargement of the HB and clump regions in the HR diagrams of our two fields. In each panel of the figure the solid lines show the luminosity level of the HB of the old stellar component inferred from the average luminosity of the RR Lyrae stars. In particular, if we use the RR Lyrae to trace the average I luminosity of the Clump of the old stellar component we derive a distance modulus for the LMC about 0.15 mag larger than obtained by Udalski (2000), and the adoption of our reddening value ($E(B-V)=0.10$ mag) would contribute further to lengthen by 0.14 mag the distance modulus of the LMC.

Finally, if we assume for the absolute magnitude of the RR Lyrae either the HB luminosity derived from the new and still unpublished Main Sequence Fitting distances of NGC6397 and NGC6752 by Gratton and collaborators, based on their ESO-VLT Large Program on GGCs, or, alternatively, values from the revised Baade-Wesselink analysis of Cacciari et al. (2000), and combine them with our $\langle V(RR) \rangle_0$ we obtain a distance modulus for the LMC of 18.47 mag, in better agreement with the "long" distance scale.

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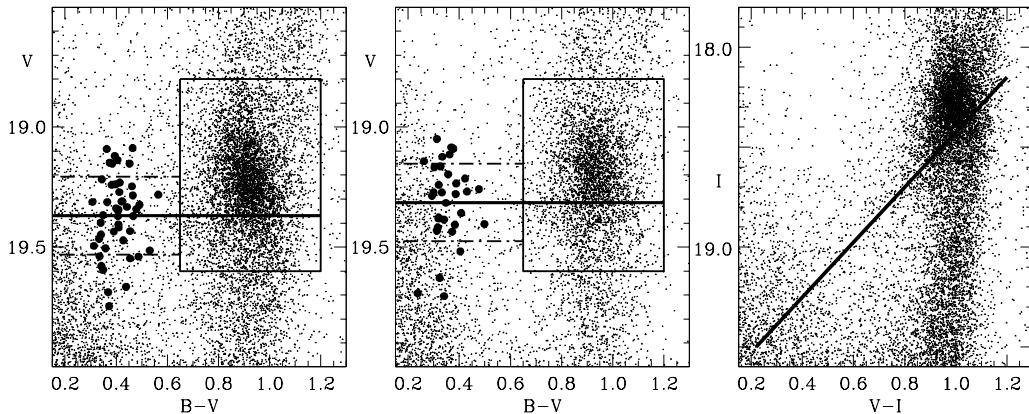


Figure 3. Enlargement of the HB and Clump regions in the V vs $B-V$ HR diagram of Field A (left panel) and B (central panel), respectively, from data taken in 1999. In the right panel the I vs $V-I$ HR diagram of Field A from the 2001 data. Filled circles mark the RR Lyrae stars which are plotted according to their intensity average magnitudes and colors. In each panel solid lines show the luminosity level of the HB of the old stellar component inferred from the average luminosity of the RR Lyrae stars. The dot-dashed lines correspond to the 1σ deviations from the average.

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